Use of Soil Texture Analysis to Predict Subsurface Fracturing in Glacial Tills and Other Unconsolidated Materials[1]

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ABSTRACT. Predicting the occurrence and development of fractures is difficult because fracturing in glacial tills and other unconsolidated materials has been observed across many geographic areas, climates, land uses, soil types, and till units. This difficulty led to a statistical investigation of historic geologic and soil data. Soil textures and fracture depths from 9 field sites and 45 soil pedons (140 sample points) were analyzed using statistical and graphical methods. When plotted on the USDA soil texture ternary diagram, the data indicate that tills having less than 10% clay or greater than 52% sand are unlikely to support fracturing; conversely tills having greater than 10% clay or less than 52% sand are more likely to do so. Based on the 95% hexagonal confidence region for soil texture data, tills with less than 55% sand, 20-65% silt, and 5-53% clay would be more likely to form fractures. The texture classes of tills predicted to sustain fracturing were mainly clay, loam, clay loam, silty clay loam, and silty clay. The depth of glacial tills having observed fractures ranged from 0.5 to 215 ft. These results are useful to explain and document how fractures are created in glacial tills and may be a useful tool for field engineers and geologists allowing them to anticipate fractures in glacial tills in Ohio and beyond.

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INTRODUCTION

Glacial tills, which cover two-thirds of Ohio, are composed of a mixture of pebbles and cobbles in a matrix of sand, silt, and clay. Fractures are present in many glacial tills (Brockman and Szabo 2000; Weatherington-Rice 2003). Fractures occur due to desiccation, freeze-thaw cycles, shearing from overriding ice, stress relief from removal of ice, and volume change from geochemical processes (Brockman and Szabo 2000). Fractures facilitate recharge to underlying aquifers but they can also provide pathways for contaminants to pass through to the ground water, resulting in ground-water contamination and threatening public health when ground water is used as a source of drinking water.

Soil texture is one of the principal factors affecting the genesis and development of fractures in glacial tills (Tornes and others 2000; Gross and Moran 1971; Steiger and Holowaychuck 1971). Tornes and others (2000) investigated how the likelihood of fractures varied depending on the relative amounts of clay, silt, and sand in unconsolidated materials and concluded that fractures were more likely to occur in glacial tills with loam, clay loam, silt loam, silty loam, silty clay, or clay textures. In northeast Ohio, the range of grain size fractions in glacial tills has been reported as 28-45% sand, 36-46% silt, and 18-35% clay, that is, predominantly a loam texture (Gross and Moran 1971). In western Ohio, soils observed to have fractures contained 2-38% sand, 30-52% silt, and 17-68% clay (Steiger and Holowaychuck 1971).

Ternary diagrams (Fig. 1) can be used for graphical and statistical interpretation of soil data. The diagrams play a central role in soil classification schemes and models of sand, silt, and clay proportions in soils (Soil Survey Staff 1993). Raw point-data are amalgamated to form the three groups, whose totals are normalized to yield ternary percentages or proportions. The data points or their arithmetic means may then be displayed in a ternary diagram. By using statistical methods, confidence regions (predictive regions) can be constructed to capture the scatter of data points in ternary diagrams using sample means and standard deviations.

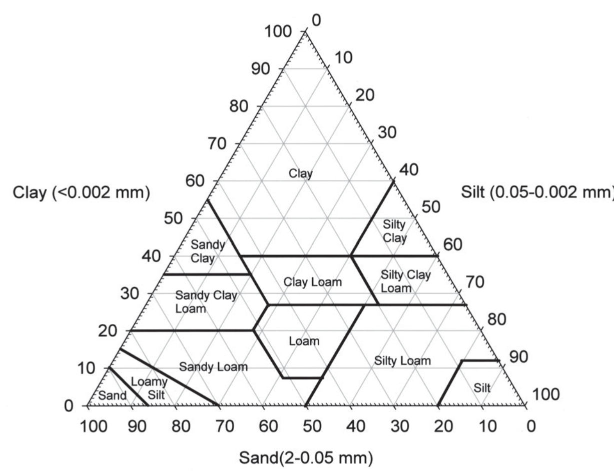

FIGURE 1. Ternary diagram of the USDA soil texture classification (Soil Survey Staff 1993).

Weltje (2002) summarized the existing methods for construction of predictive regions in ternary diagrams in various fields of sedimentary petrology. The components (for example, rock fragments, sand, and sandstone) resulting from weathering and transport from parent materials were not independent of each other. He stated that multivariate statistical methods might be more suitable than univariate statistical methods (so-called hexagonal fields of compositional variation) in sedimentary

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petrology. Based on the multivariate normal approximation, he developed a computer FORTRAN program (Weltje 1993) to determine confidence regions in ternary diagrams.

A hexagonal field of compositional variation in ternary diagrams, introduced by Stevens and others (1956), was approximated by univariate normal distribution. One assumption of univariate statistics is that the components are independent of each other. These hexagonal fields of variation have been used in sedimentary petrology (Ingersoll 1978; Ingersoll and Suczek 1979; Weltje 2002).

Fracture occurrence can be correlated with soil depth in glacial tills and unconsolidated soils. Several researchers (Brockman and Szabo 2000; McKay and others 1993) investigated the depth of soils having fractures. McKay and others (1993) found that fracture zones have been observed at depths ranging from a few meters to tens of meters in Ontario, Canada. Brockman and Szabo (2000) reported that fracture zones in Ohio have been observed at depths from 0.5-50.5 feet.

It is difficult to predict the occurrence and development of fractures. No statistical analysis of soil textural data (sand-silt-clay contents) in glacial till or unconsolidated soil having fractures has been attempted until now. Another confounding factor is that fractures cover a wide geographic area in Ohio. The soil textural data observed to sustain fractures in glacial tills are very diverse with different soil types (Tornes and others 2000) and different till units (Teller 1970). Tornes and others (2000) presented the range of sand, silt, and clay contents in a ternary diagram and soil texture classes for 95 glacially derived soil types having fractures in Ohio. However, their research did not include statistical analyses of these data or models to predict fracture creation and development in other soils.

The hypothesis of this research was that the likelihood of fractures is dependent on soil texture and depth and can be quantified statistically. The goals of this research were to investigate how the occurrence of fractures in natural settings varies depending on soil texture and depth, and to quantify the probability of fracturing through statistical analysis, which could serve as a useful tool to anticipate and investigate fractures in glacial tills in Ohio.

MATERIALS AND METHODS

Soil data were collected from historic references that documented fractures in glacial tills or unconsolidated materials in Ohio. The references were complied from published sources (Brockman and Szabo 2000; Tornes and others 2000; Lloyd 1998; Teller 1970; Weatherington-Rice 2003) and from published and unpublished reports collected by Bennett and Williams Environmental Consultants Inc., Columbus, OH. Nine sites where documented fractures were present were identified (Table 1). Soil textures (the portion of clay, silt, and sand composing the soil matrix) and depth information were collected from soil borings, backhoe excavations, and natural stream cuts in the sites. The references included the geological and hydrological information for each site. Soil textures classified by the proportions of sand (2.0 – 0.05 mm), silt (0.05 – 0.002 mm), and clay (<0.002 mm) at the sites were determined by USDA classification from grain size distribution analysis (Soil Survey Staff 1993). This study added these data collected from the nine field sites to the 45 sampled pedons reported in Tornes and others (2000). The combined soil texture data were analyzed using statistical and graphical methods. MINITAB™ (MINITAB Inc. 2000) was used for summary descriptive analysis including mean and standard deviations and normality tests. The soil textures were plotted in ternary diagrams using Sigma Plot (SPSS Inc. 2002). For depth analysis, the data were collected from the nine field sites and from Brockman and Szabo (2000).

The statistical (predictive) models were defined by statistically derived confidence regions. The confidence regions were used to predict the range of variation of the entire data set in a ternary diagram. Confidence regions of 90, 95, and 99% for ternary texture compositions (sand, silt, clay) were constructed using both bivariate and univariate statistical methods.

The bivariate statistical method involved log-ratio transformation procedures and a computer FORTRAN program developed by Weltje (1993) for construction of 90, 95, and 99% confidence regions. Any compositional data that included zero values were eliminated from the raw data set, and the remaining data were analyzed using the FORTRAN program. The output points (40 points) forming the boundary of each confidence region were plotted on a ternary diagram, along with the soil texture data.

Using log-ratio transformation procedures, ternary compositional data (sand, silt, clay) were divided by one component (in this case, silt) as the denominator. These components (sand/silt, silt/silt, clay/silt) were then transformed logarithmically. A set of log-ratios [log (sand/silt), log (clay/silt)] were plotted with confidence ellipses of 90, 95, and 99% using SAS software (SAS Institute Inc. 2003). Forty points randomly taken from within the confidence ellipse lines were transformed back using the inverse log-ratio transformations. The confidence regions for those 40 points in a ternary diagram were constructed using SigmaPlot (SPSS Inc. 2002).

A hexagonal field of compositional variation was based on the assumption of a univariate normal distribution. A hexagonal field of variation was calculated by means of normal approximation including arithmetic means, standard deviations, and upper or lower confidence limits ($C_{U\text{ or }L}$ = mean ± standard deviation × $t_{df:\alpha/2}$). The confidence boundaries thus generated on a ternary plot are a pair of parallel lines bracketing the arithmetic mean (Philip and others 1987; Howard 1994). The orientation of each pair of lines is parallel to the side of the diagram that is opposite to that component's vertex. The predicted upper and lower confidence boundaries of each component were labeled with subscripts U and L. From these boundaries, a set of six ternary compositions were constructed as a matrix which defines the hexagon:

$$\begin{pmatrix} 100 - Silt_L - Clay_U & Silt_L & Clay_U \\ Sand_L & 100 - Sand_L - Clay_U & Clay_U \\ Sand_L & Silt_U & 100 - Sand_L - Silt_U \\ 100 - Silt_U - Clay_L & Silt_U & Clay_L \\ Sand_U & 100 - Sand_U - Clay_L & Clay_L \\ Sand_U & Silt_L & 100 - Sand_U - Silt_L \end{pmatrix}$$

where 100 (%) is the constant-sum value. The six ternary compositions were drawn on a ternary diagram using Sigma Plot (SPSS Inc. 2002). The confidence boundaries were illustrated with different line shapes: "straight" for so-called true hexagonal confidence regions and "spline" for the smoothed hexagonal confidence regions.

RESULTS AND DISCUSSION

Figure 2 shows the soil texture data (a total of 140 points) plotted on an USDA ternary diagram for 9 sites having fractures and 45 pedons reported in Tornes and others (2000). When plotted on the USDA soil texture ternary diagram, the data suggest that tills having less than 10% clay or greater than 52% sand are unlikely to support fracturing; conversely, tills having greater than 10% clay or less than 52% sand are more likely to do so (the unshaded region of Fig. 2). The actual ranges of sand, silt, and clay in fractured field sites were 0-52%, 25-90% and 10-72%, respectively. The fracture data are located in mainly loam, clay loam, and clay soil texture regions, corresponding to what was observed by Tornes and others (2000).

Figure 3 shows the 90, 95, and 99% confidence regions constructed using a computer FORTRAN program developed by Weltje (1993). The confidence regions were triangular-shaped and captured most data points but extended well past the areas of observed data, including sand, loamy sand, sandy loam soil textures, which are not known to support fracturing. The 95% confidence ellipse generated by log-ratio transformation included an unwanted area between 0.25 and 0.75 in log (sand/silt) because of fundamental statistical prob-

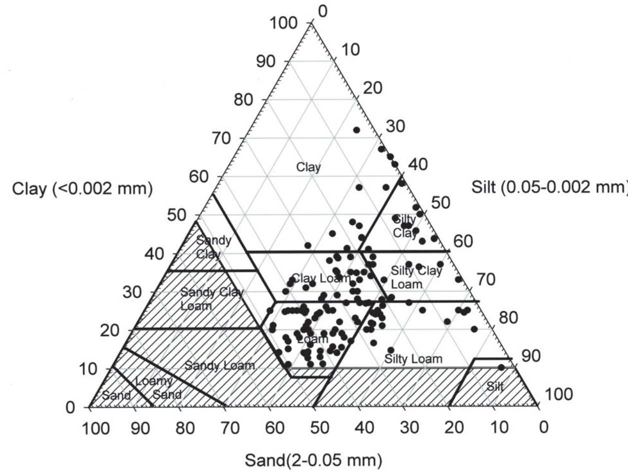

FIGURE 2. Soil texture data for 140 glacially-derived soil and till samples observed to have fracturing. The shaded area represents those textures that are unlikely to support fracturing.

TABLE 1

Description of the sites.

Site Name	Means of Observations	Site Location	References
CECOS Hazardous Waste Landfill	Borings	Clermont County	Weatherington-Rice (2003)
Envirosafe Hazardous Waste Landfill	Borings and water line trenches	Lucas County, City of Oregon	Unpublished report (B&W file)
Tremont and Proposed ClarkCo Solid Waste Landfills	Borings and excavations	Clark County, North and west of Tremont City	Unpublished report (B&W file)
Countywide recycling & disposal facility lateral & vertical expansion	Borings	Stark County	Unpublished report (B&W file)
Willow Creek Landfill	Borings and excavations	Portage County	Unpublished report (B&W file)
Proposed Solid Waste Landfill	Borings	Allen County, Spencerville	Unpublished report (B&W file)
Backbone Creek Till Cut	Natural cut	Clermont County, North bank Back Bone Creek	Teller (1970)
London Correctional Institute	Borings	Madison County	Lloyd (1999)
Graessle Road Till Cut	Natural cut	Franklin County	Lloyd (1999)

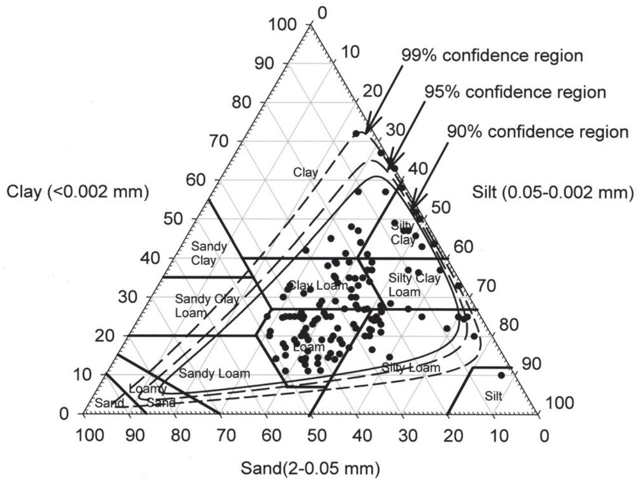

FIGURE 3. Confidence regions of 90, 95, and 99% (140 data points and 40 confidence region boundary points) based on Weltje (1993) method.

lems with the data (no data existed in this area). The construction of the confidence ellipse was based on means and standard deviations to determine the major and minor axes. The unwanted zone resulted in the acute triangular confidence regions of the untransformed data in Figure 3.

Figures 4 and 5 show the soil texture data (140 points) for the field sites with true hexagonal and with splined hexagonal confidence regions, respectively. The texture classes of tills predicted to sustain fracturing were mainly clay, loam, clay loam, silty clay loam, and silty clay. As shown in Figure 4, confidence regions of 90, 95, and 99% were constructed using hexagonal fields of variance. Given standard practice in geological sciences and environmental engineering, the 95% confidence region was chosen for the statistical model, corresponding to a significance level of 0.05. Based on the 95% hexagonal confidence region, tills with less than 55% sand, 20-65% silt, and 5-53% clay would be predicted to have fractures. It is important to note that the model gives an upper limit to the clay percentage; however that is probably an artifact of the statistical method. It is more likely that there is no real upper limit on clay content, and that 100% clay will indeed support fracturing.

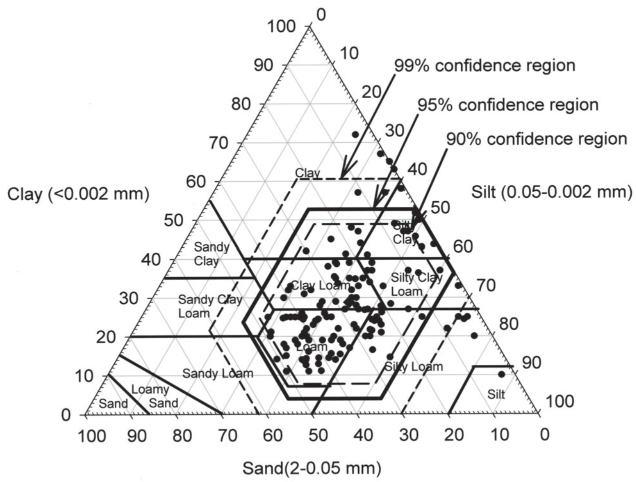

FIGURE 4. True hexagonal confidence regions of 90, 95, and 99% (140 data points and 6 confidence region boundary points).

Table 2 shows summary statistics of data on depths of tills observed to have fractures at eight of the nine field sites investigated. When this dataset was combined with the data presented in Brockman and Szabo (2000), the depths ranged from 0.5 to 215 ft. This corresponds well to data from McKay and others (1993).

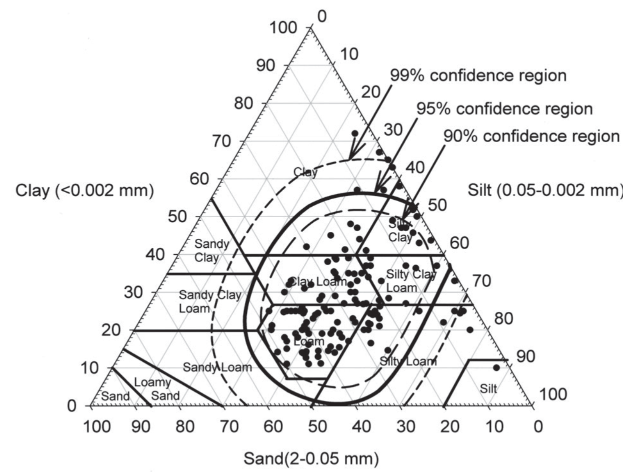

FIGURE 5. Splined hexagonal confidence regions of 90, 95 and 99% (140 data points and 6 confidence region boundary points).

SUMMARY AND CONCLUSIONS

Data on glacial till sites having observed fractures were collected from historical sources (140 points, covering 54 sites and/or soil pedons). When plotted on an USDA ternary diagram, the data indicate that tills having less than 10% clay or greater than 52% sand are unlikely to support fracturing; conversely tills having greater

TABLE 2

Depths of observed fractures at the sites.

Site name	Range (ft)
CECOS Hazardous Waste Landfill	4.8 - 129.0
Envirosafe Hazardous Waste Landfill	0.7 - 15.8
Tremont and Proposal ClarkCo Solid Waste Landfills	1.5 - 145.2
Countywide recycling & disposal facility lateral & vertical expansion	5.0 - 74.5
Backbone Creek Till Cut	2.5 - 31.0
London Correctional Institute	5.0 - 215.0
Graessle Road Till Cut	8.3 - 16.4
OSU Molly Caren Agricultural Center	0.5 - 50.5

than 10% clay or less than 52% sand are more likely to do so. Based on the 95% hexagonal confidence region, tills with less than 55% sand, 20–65% silt, and 5–53% clay can be predicted at a 0.05 significance level to have fractures. The soil textural classes predicted to sustain fracturing were clay, loam, clay loam, silty clay loam, and silty clay. The depth of fractures observed in glacial tills was 0.5 to 215 ft.

Future research is planned including laboratory fracturing experiments to extend the dataset to cover a wider range of possible soil textures and to improve the predictive model developed here. These predictive models could be applied to future drilling sites in Ohio, and the data collected could be used to further validate the model.

Statistical models and predictive formulas can be useful to explain and document how fractures are created in glacial tills. These can be useful tools for field engineers, geologists, and soil scientists, which allow them to anticipate fractures in glacial tills in Ohio and beyond.

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